Evidence for an anomalous like-sign dimuon charge asymmetry at D0

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On Behalf of D0 Collaboration

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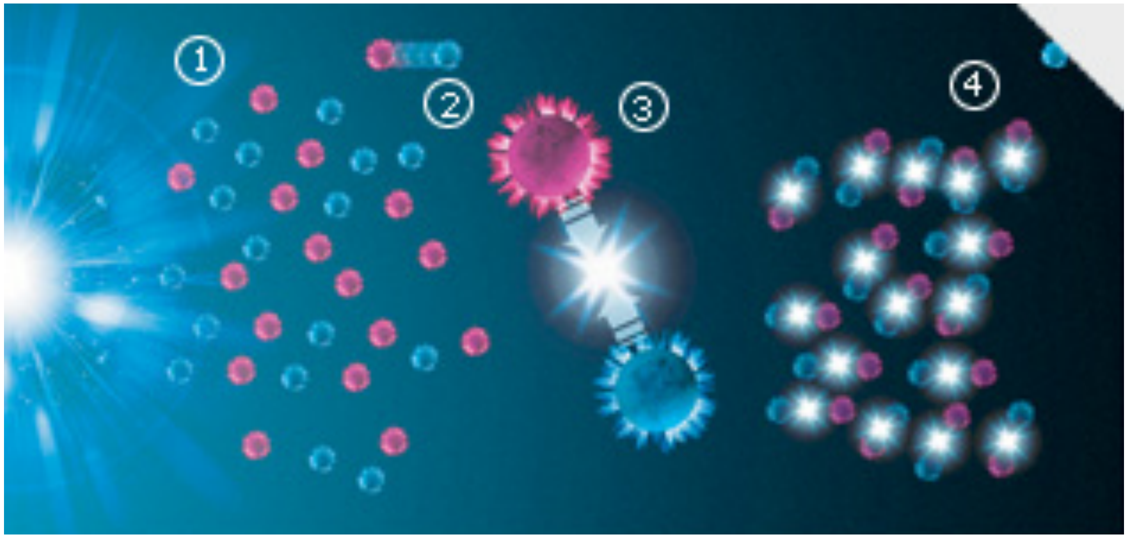
Universe Today



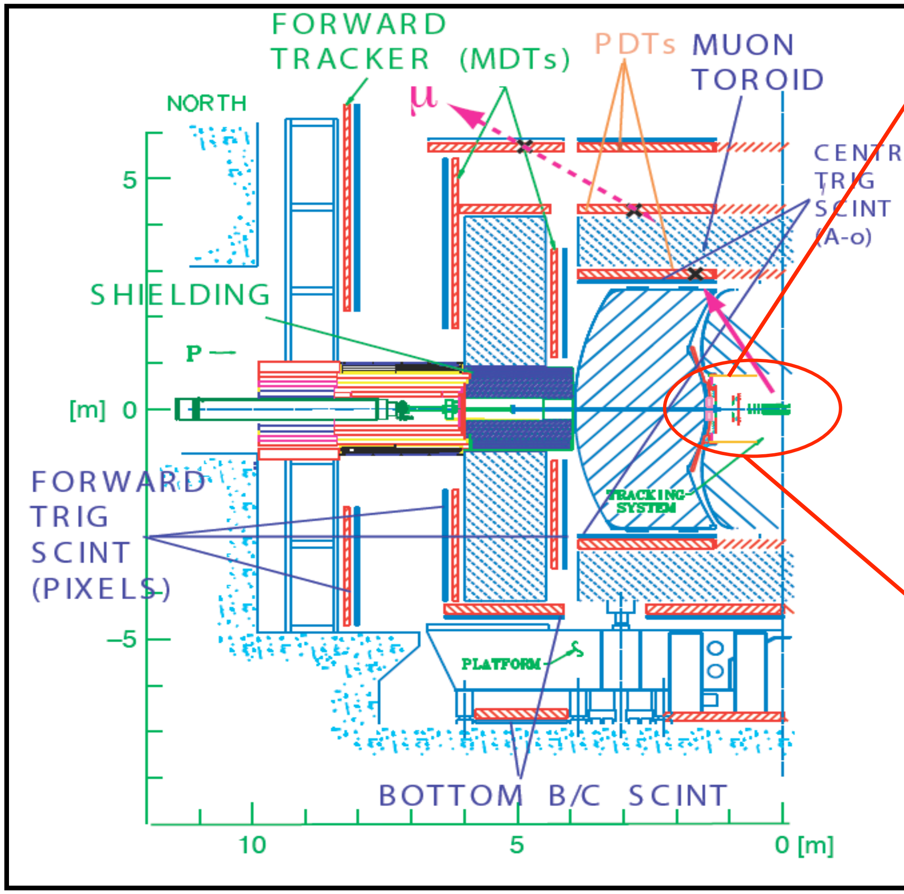
$$\frac{n_{\mathcal{B}}}{n_{\gamma}} = (6.2 \pm 0.2)\times 10^{-10}$$

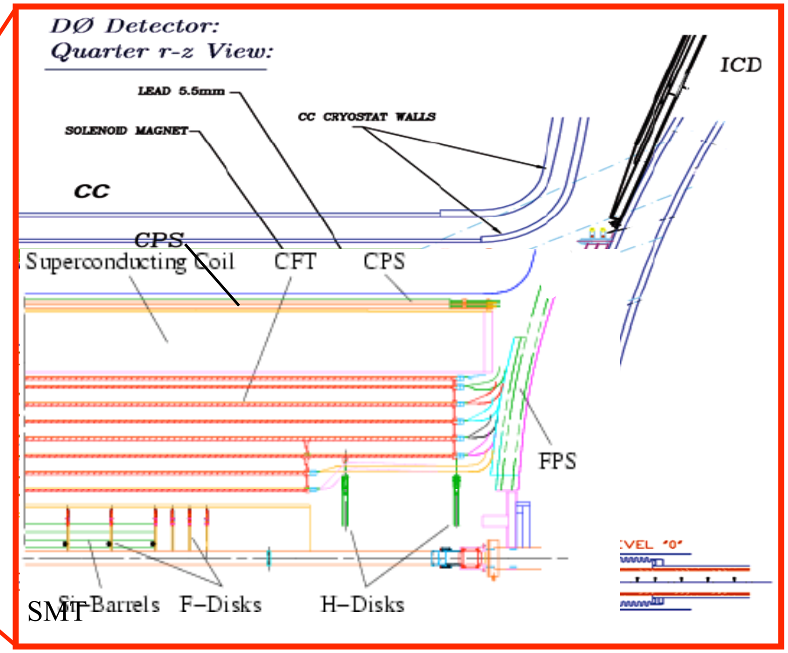
WMAP

- ~4% Matter
- Baryon number violation
- CP violation
- Deviation from equilibrium
  - A.D. Sakharov

- Current estimate from SM 10^{-20}
- 10 orders of magnitude difference

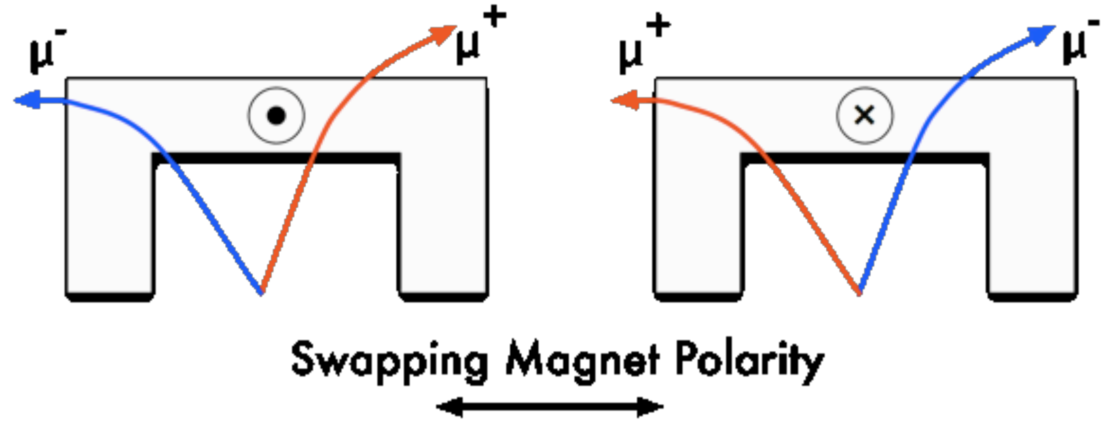
DØ Detector





- General purpose detector
- Excellent coverage of tracking and muon systems ($|\eta|<2$)
- Excellent vertex resolution
- 2T Solenoid, muon system toroid

Reversal of Magnet Polarities



- Polarities of DØ solenoid and toroid are reversed regularly
- Trajectory of the negative particle becomes exactly the same as the trajectory of the positive particle with the reversed magnet polarity
- Analyzing 4 samples with different polarities (++, −−, +−, −+) the difference in the reconstruction efficiency between positive and negative particles is minimized

Changing polarities is an important feature of DØ detector, which reduces significantly systematics in charge asymmetry measurements

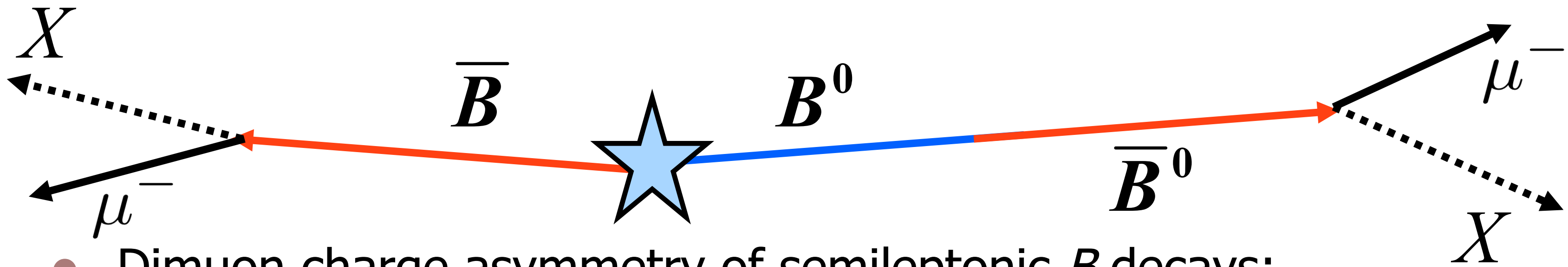
Past Measurements

- "Measurement of the Like-Sign Dimuon Charge Asymmetry in pp bar Collisions at √s= 1.8 TeV"
  - Not published, 1997
  - Influenced decisions made for Run II detector upgrade
- "Measurement of the CP-Violation Parameter of B^0 Mixing and Decay with pp→ μ μ X Data"

$$A_{SL} = -0.0092 \pm 0.0044 \pm 0.0032$$

  - 1 fb^{-1}, Phys. Rev. D **74**, 092001 (2006)
- "Measurement of the Charge Asymmetry in Semileptonic B_s^0 Decays"
  - 1.3 fb^{-1}, Phys. Rev. Lett. 98, 151801 (2007)
- "Search for CP Violation in Semileptonic B_s^0 Decays"
  - 5 fb^{-1}, arXiv.org:0904.3907

Dimuon charge asymmetry



- Dimuon charge asymmetry of semileptonic *B* decays:

$$A_{sl}^{b} \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

  - N_b^{++}, N_b^{--} – number of events with two *b* hadrons decaying semileptonically and producing two muons of the same charge
  - One muon comes from direct semileptonic decay $b \to \mu^- X$
  - Second muon comes from direct semileptonic decay after neutral *B* meson mixing: $B^0 \to \overline{B}^0 \to \mu^- X$

Semileptonic charge asymmetry

- A^b_{sl} is equal to the charge asymmetry of "wrong sign" semileptonic B decays:

$$a^b_{sl} \equiv \frac{\Gamma(\overline{B} \to \mu^+ X) - \Gamma(B \to \mu^- X)}{\Gamma(\overline{B} \to \mu^+ X) + \Gamma(B \to \mu^- X)} = A^b_{sl}$$

  - See Y. Grossman, Y. Nir, G. Raz, PRL 97, 151801 (2006)
  - "Right sign" decay is $B \to \mu^+ X$
  - "Wrong sign" decays can happen only due to flavour oscillation in B_d and B_s
  - Semileptonic charge asymmetry can be defined separately for B_d and B_s :

$$a^q_{sl} \equiv \frac{\Gamma(\overline{B}^0_q \to \mu^+ X) - \Gamma(B^0_q \to \mu^- X)}{\Gamma(\overline{B}^0_q \to \mu^+ X) + \Gamma(B^0_q \to \mu^- X)}; \quad q = d, s$$

$A^b{}_{\mathrm{sl}}$ at the Tevatron

- Since both B_d and B_s are produced at the Tevatron, $A^b{}_{\mathrm{sl}}$ is a linear combination of $a^d{}_{\mathrm{sl}}$ and $a^s{}_{\mathrm{sl}}$:

$$A_{sl}^{b} = (0.506 \pm 0.043)a_{sl}^{d} + (0.494 \pm 0.043)a_{sl}^{s}$$

  - Need to know production fractions of B_d and B_s mesons at the Tevatron
  - Measured by the CDF experiment
- Standard model predicts a very small value of $A^b{}_{\mathrm{sl}}$:

$$A_{sl}^{b} = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}$$

  - using prediction of $a^d{}_{\mathrm{sl}}$ and $a^s{}_{\mathrm{sl}}$ from A. Lenz, U. Nierste, hep-ph/0612167

Analysis Strategy

1 Experimentally, we measure two quantities:

- Like-sign dimuon charge asymmetry:

$$A \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}}$$

- Inclusive muon charge asymmetry:

$$a \equiv \frac{n^{+} - n^{-}}{n^{+} + n^{-}}$$

- N^{++}, N^{--} – the number of events with two like-sign dimuons
- n^{+}, n^{-} – the number of muons with given charge
- Both A and a linearly depend on the charge asymmetry A^{b}_{sl}

$$a = k\, A^{b}_{sl} + a_{bkg}$$

$$A = K\, A^{b}_{sl} + A_{bkg}$$

2 Determine the background contributions A_{bkg} and a_{bkg}

3 Find the coefficients K and k

4 Exctract A^{b}_{sl}

Subtract Background to Extract $A^b{}_{sl}$

$$a = k\, A^b_{sl} + a_{bkg}$$

$$A = K\, A^b_{sl} + A_{bkg}$$

- The same background processes contribute to both A_{bkg} and a_{bkg}
  - Kaon and pion decays $K^+ \to \mu^+ \nu$, $\pi^+ \to \mu^+ \nu$ or punch-through
  - proton punch-through
  - False track associated with muon track
  - Asymmetry of muon reconstruction
  - Measured directly in data, allows to reduce systematic uncertainty
- Therefore, the uncertainties of A_{bkg} and a_{bkg} are correlated
- We take advantage of the correlated background contributions, and obtain $A^b{}_{sl}$ from the linear combination:

$$A' \equiv A - \alpha\, a$$

  - Coefficient α is selected such that the total uncertainty of $A^b{}_{sl}$ is minimized

Event selection

- Inclusive muon sample:
  - Charged particle identified as a muon
  - $1.5 < p_T < 25$ GeV
  - muon with $p_T < 4.2$ GeV must have $|p_Z| > 6.4$ GeV
  - $|\eta| < 2.2$
  - Distance to primary vertex: <3 mm in axial plane; < 5 mm along the beam
- Like-sign dimuon sample:
  - Two muons of the same charge
  - Both muons satisfy all above conditions
  - Primary vertex is common for both muons
  - $M(\mu\mu) > 2.8$ GeV to suppress events with two muons from the same *B* decay

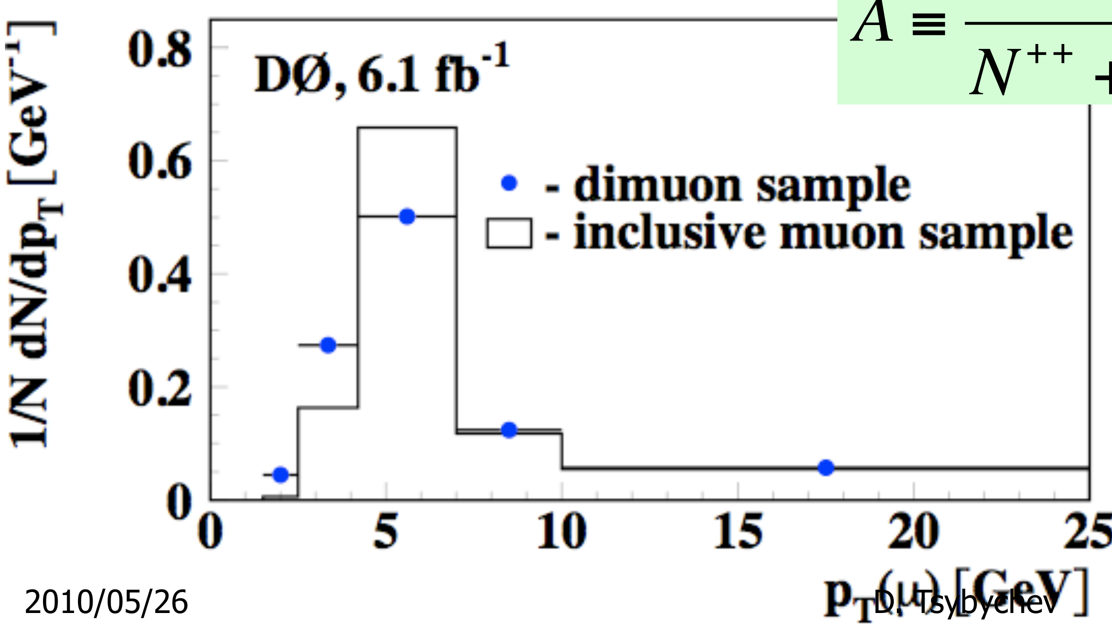
Raw Asymmetries

- We measure:
  - From 1.495×10^9 muons in the inclusive muon sample

$$a \equiv \frac{n^+ - n^-}{n^+ + n^-} = (+0.955 \pm 0.003)\%$$

  - 3.731×10^6 events in the like-sign dimuon sample

$$A \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}} = (+0.564 \pm 0.053)\%$$



Asymmetries in Background

$$a_{bkg} = f_k a_k + f_\pi a_\pi + f_p a_p + (1 - f_{bkg})\delta$$
$$A_{bkg} = F_k A_k + F_\pi A_\pi + F_p A_p + (2 - F_{bkg})\Delta$$

- $\boldsymbol{f_K}$, $\boldsymbol{f_\pi}$, and $\boldsymbol{f_p}$ are the fractions of kaons, pions and proton identified as a muon in the inclusive muon sample
  - $\boldsymbol{a_K}$, $\boldsymbol{a_\pi}$, and $\boldsymbol{a_p}$ are the charge asymmetries of kaon, pion, and proton tracks in the inclusive muon sample
- $\boldsymbol{\delta}$ is the charge asymmetry of muon reconstruction
- $\boldsymbol{f_{bkg}} = f_K + f_\pi + f_p$
- $\boldsymbol{F_K}$, $\boldsymbol{F_\pi}$, and $\boldsymbol{F_p}$ are the fractions of kaons, pions and protons identified as a muon in the like-sign dimuon sample
  - $\boldsymbol{A_K}$, $\boldsymbol{A_\pi}$, and $\boldsymbol{A_p}$ are the charge asymmetries of kaon, pion, and proton tracks
- $\boldsymbol{\Delta}$ is the charge asymmetry of muon reconstruction
- $\boldsymbol{F_{bkg}} = F_K + F_\pi + F_p$

Kaon Detection Asymmetry

- The largest background asymmetry, and the largest background contribution comes from the charge asymmetry of kaon track identified as a muon (a_K, A_K)
- Interaction cross section of K^+ and K^- with the detector material is different, especially for kaons with low momentum
  - e.g., for $p(K)$ = 1 GeV: $\sigma(K^- d) \approx 80\ \mathrm{mb}$

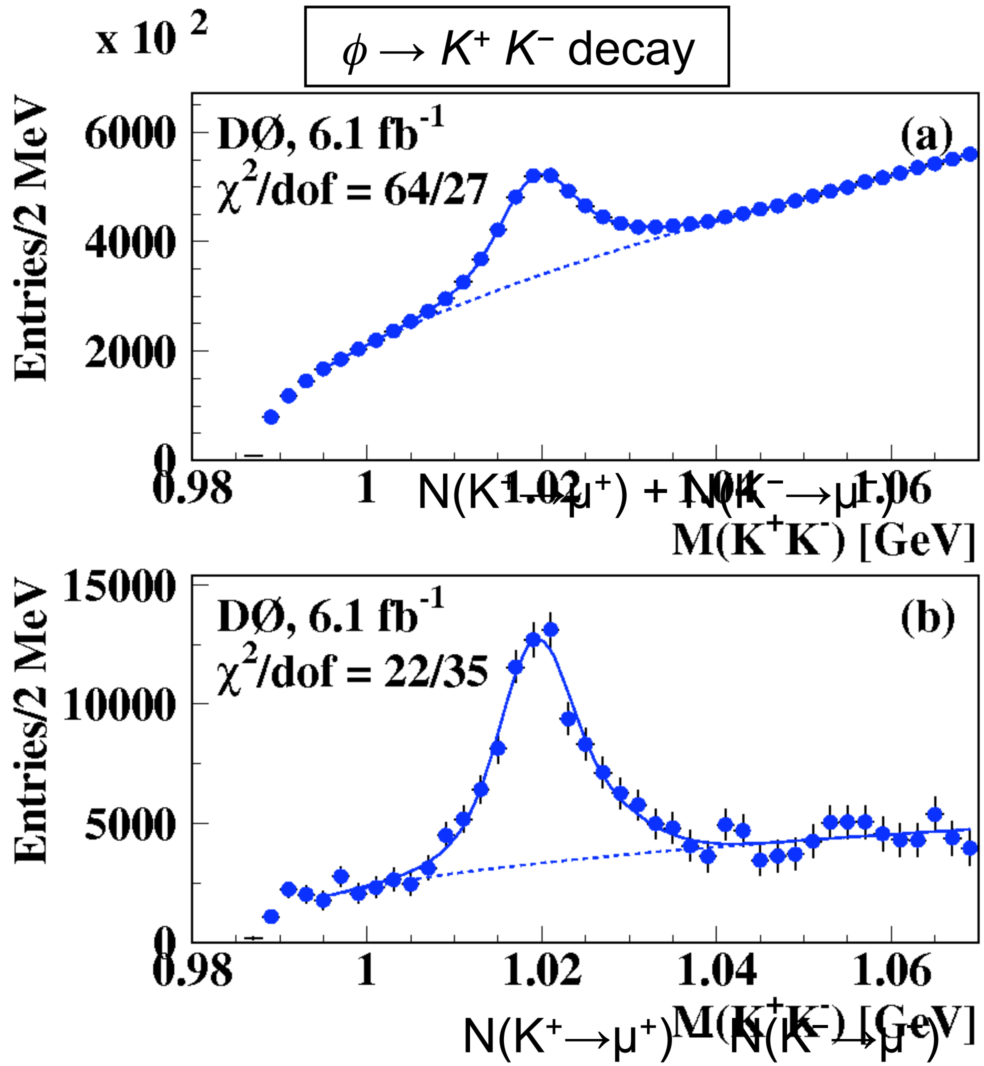
    $\sigma(K^+ d) \approx 33\ \mathrm{mb}$
- It happens because the reaction $K^- N \rightarrow Y\pi$ has no $K^+ N$ analogue
  - Detector made of matter
  - K^+ meson travels further than K^- in the detector, and has more chance to decay to a muon or to punch-through
- Therefore, the asymmetries a_K, A_K **should be positive**
- All other background asymmetries are found to be about ten times less

Measurement of Kaon Asymmetry

- Define sources of kaons:

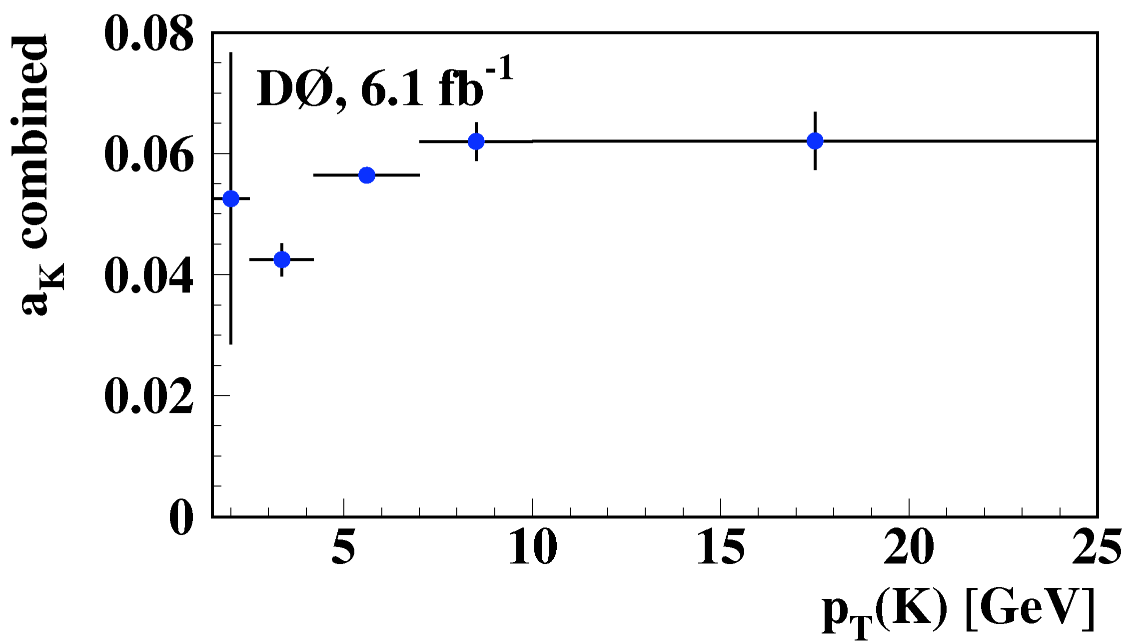
$$K^{*0} \rightarrow K^+\pi^-$$
$$\phi(1020) \rightarrow K^+K^-$$

- Require that the kaon is identified as a muon
- Build the mass distribution separately for positive and negative kaons
- Compute asymmetry in the number of observed events



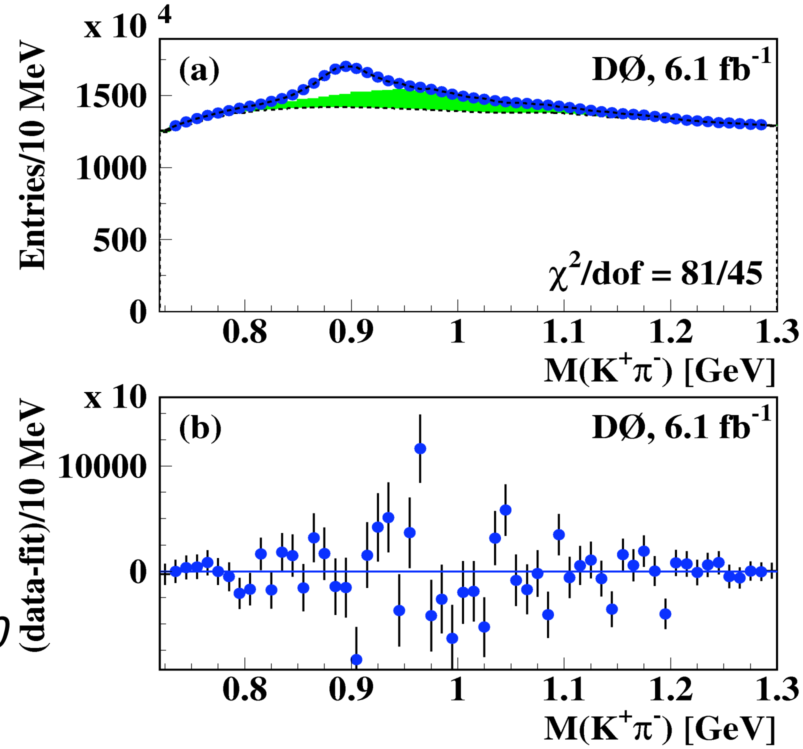
Measurement of Kaon Asymmetry

- Results from $K^{*0} \rightarrow K^+\pi^-$ and $\phi(1020) \rightarrow K^+K^-$ agree well
  - For the difference between two channels: χ^2/dof =5.4/5
- We combine the two channels together:



Measurement of f_K, F_K

- Fractions f_K , F_K are measured using the decays $K^{*0} \to K^+\pi^-$ and selected in the inclusive muon and like-sign dimuon samples respectively;
- Kaon is required to be identified as a muon;
- We measure fractions $f_{K^{*0}}$, $F_{K^{*0}}$



$$f_K = \frac{N(K_S)}{N(K^{*+})} f_{K^{*0}}$$

$$F_K = \frac{N(K_S)}{N(K^{*+})} F_{K^{*0}}$$

Use simulation to confirm pion reconstruction ε is the same for K^{*+} and K^{*0} if K^+/K_S is reconstructed

Measurement of a_π, a_p

- The asymmetries a_π , a_p are measured using the decays $K_S \to \pi^+ \pi^-$ and $\Lambda \to p\, \pi^-$ respectively

	a_K	a_π	a_p
Data	$(+5.51 \pm 0.11)\%$	$+(0.25 \pm 0.10)\%$	$(+2.3 \pm 2.8)\%$

- These are all determined in "muon" p_T bins
- Asymmetries in the dimuon sample are derived taking into account the slightly different muon p_T distributions

$$F_K A_K = \sum_{i=0}^{4} F_\mu^i F_K^i a_K^i$$

Measurement of f_π, F_π, f_p, F_p

- We obtain f_π , F_π as:

$$f_\pi = f_K \frac{P(\pi \to \mu)}{P(K \to \mu)} \frac{n_\pi}{n_K}$$

$$F_\pi = F_K \frac{P(\pi \to \mu)}{P(K \to \mu)} \frac{N_\pi}{N_K}$$

- We use as an input:
  - Measured fractions f_K , F_K
  - Ratio of probabilities for charged pion and kaon to be identified as a muon $P(\pi \to \mu) / P(K \to \mu)$ is measured using decays $K_S \to \pi^+ \pi^-$ and $\phi(1020) \to K^+ K^-$;
  - Ratio of multiplicities of pion and kaon n_π / n_K (N_π / N_K) in QCD events taken from simulation
    - Systematic uncertainty due to multiplicities: 4%
  - The decay $\Lambda \to p\pi^-$ is used to identify a proton and to measure $P(p \to \mu)/P(K \to \mu)$, f_p , F_p

Summary of Background Composition

$$f_{bkg} = f_k + f_\pi + f_p$$

- We get the following background fractions in the inclusive muon events:

	$(1-f_{bkg})$	f_K	f_π	f_p
MC	(59.0±0.3)%	(14.5±0.2)%	(25.7±0.3)%	(0.8±0.1)%
Data	(58.1±1.4)%	(15.5±0.2)%	(25.9±1.4)%	(0.7±0.2)%

  - Uncertainties for both data and simulation are statistical
  - Simulation fractions are given as a cross-check only, and **are not used in the analysis**
  - Good agreement between data and simulation within the systematic uncertainties assigned

Muon Reconstruction Asymmetry

- We measure the muon reconstruction asymmetry using $J/\psi \to \mu\mu$ events
- Average asymmetries δ and Δ are:

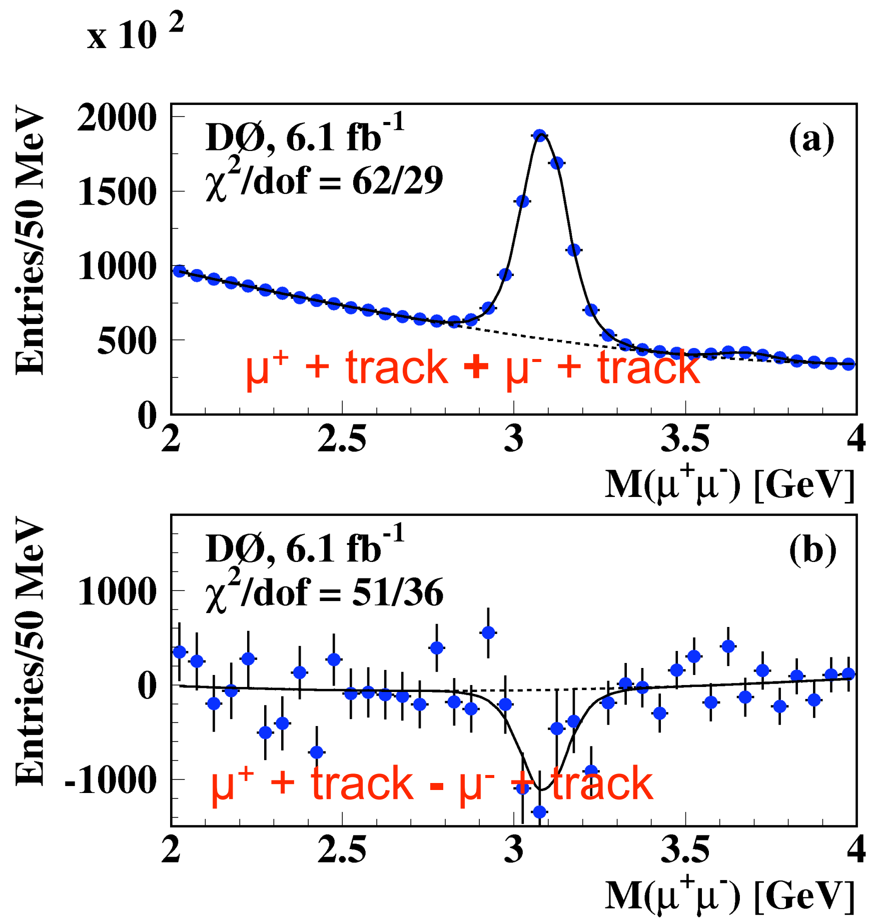
$$\delta = (-0.076 \pm 0.028)\%$$

$$\Delta = (-0.068 \pm 0.023)\%$$

- To be compared with:

$$a = (+0.955 \pm 0.003)\%$$

$$A = (+0.564 \pm 0.053)\%$$



Such small values of charge reconstruction asymmetries are a direct consequence of the regular reversal of magnet polarities during data taking

Summary of Background Contribution

$$a_{bkg} = f_k a_k + f_\pi a_\pi + f_p a_p + (1 - f_{bkg})\delta$$

$$A_{bkg} = F_k A_k + F_\pi A_\pi + F_p A_p + (2 - F_{bkg})\Delta$$

	$f_K a_K$ (%) or $F_K A_K$ (%)	$f_\pi a_\pi$ (%) or $F_\pi A_\pi$ (%)	$f_p a_p$ (%) or $F_p A_p$ (%)	$(1-f_{bkg})\delta$ (%) or $(2-F_{bkg})\Delta$ (%)	a_{bkg} or A_{bkg}
Inclusive	0.854±0.018	0.095±0.027	0.012±0.022	−0.044±0.016	0.917±0.045
Dimuon	0.828±0.035	0.095±0.025	0.000±0.021	−0.108±0.037	0.815±0.070

- All uncertainties are statistical
- Notice that background contribution is similar for inclusive muon and dimuon sample: $A_{bkg} \approx a_{bkg}$

Signal Contribution

- After subtracting the background contribution from the "raw" asymmetries *a* and *A*, the remaining residual asymmetries are proportional to A^b_{sl}

$$k\,A^b_{sl} = a - a_{bkg}$$
$$K\,A^b_{sl} = A - A_{bkg}$$

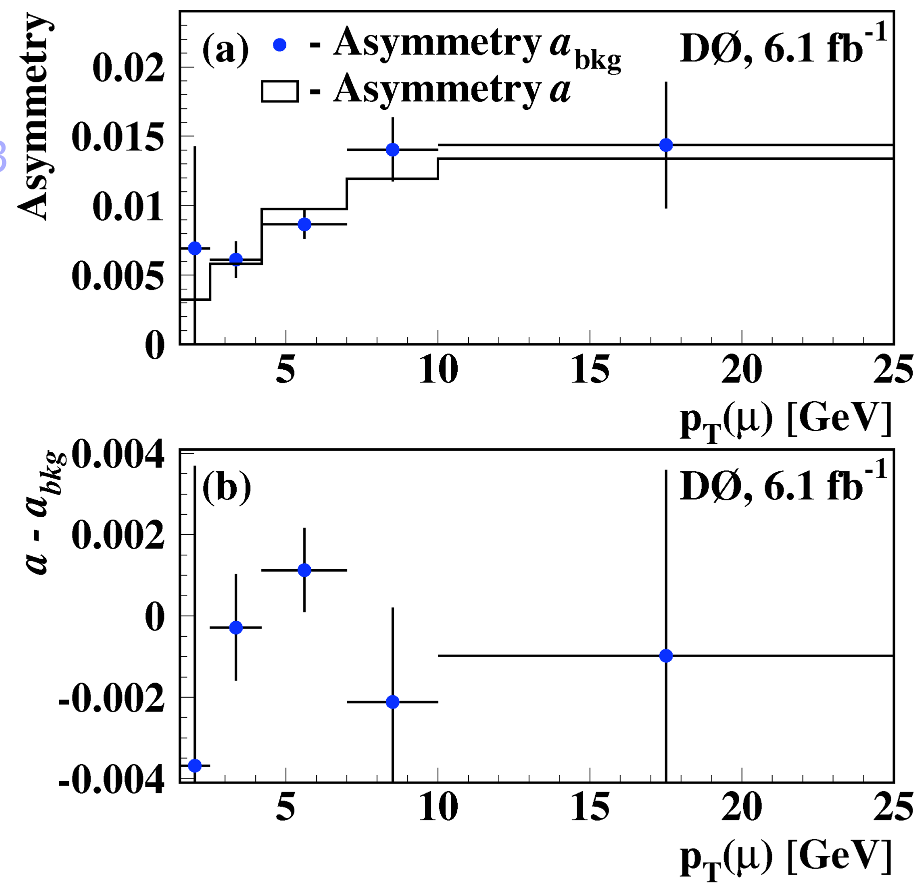
- Many decays of b- and c-quark contribute to inclusive muon and like-sign dimuon sample
  - dilute the values of *a* and *A* by contributing to the denominator of these asymmetries
  - Only oscillation term produces asymmetry
- k,K determined from the simulation

	Process	Weight
T_1	$b \to \mu^- X$	$w_1 \equiv 1.$
T_{1a}	$b \to \mu^- X$ (nos)	$w_{1a} = (1-\chi_0)w_1$
T_{1b}	$\bar{b} \to b \to \mu^- X$ (osc)	$w_{1b} = \chi_0 w_1$
T_2	$b \to c \to \mu^+ X$	$w_2 = 0.113 \pm 0.010$
T_{2a}	$b \to c \to \mu^+ X$ (nos)	$w_{2a} = (1-\chi_0)w_2$
T_{2b}	$\bar{b} \to b \to c \to \mu^+ X$ (osc)	$w_{2b} = \chi_0 w_2$
T_3	$b \to c\bar{c}q$ with $c \to \mu^+ X$ or $\bar{c} \to \mu^- X$	$w_3 = 0.062 \pm 0.006$
T_4	$\eta, \omega, \rho^0, \phi(1020), J/\psi, \psi' \to \mu^+\mu^-$	$w_4 = 0.021 \pm 0.001$
T_5	$b\bar{b}c\bar{c}$ with $c \to \mu^+ X$ or $\bar{c} \to \mu^- X$	$w_5 = 0.013 \pm 0.002$
T_6	$c\bar{c}$ with $c \to \mu^+ X$ or $\bar{c} \to \mu^- X$	$w_6 = 0.660 \pm 0.077$

$$k = 0.041 \pm 0.003$$
$$K = 0.342 \pm 0.023$$

Closure Test

- The value of a is mainly determined by the background asymmetry a_{bkg}
  - A^b_{sl} in is suppressed by k = 0.041±0.003
- Construct a_{bkg} from
  f_K, f_π, f_p, a_K, a_π, a_p and δ,
  verify how well does it describe the observed asymmetry a
- We compare a and a_{bkg} as a function of muon p_T
- We get χ^2/dof = 2.4/5 for the difference between these two distributions



Excellent agreement between the expected and observed values of a, including a p_T dependence

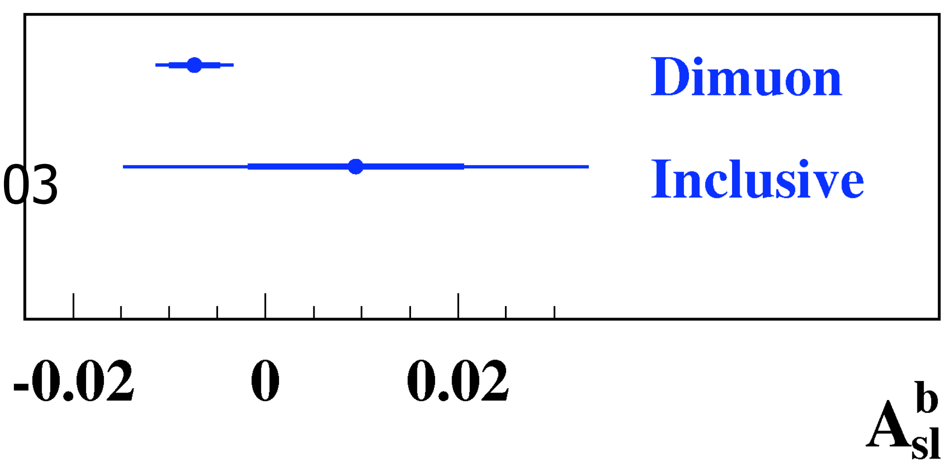
Bringing everything together

- Using all results on background and signal contribution we get two separate measurements of A^b_{sl} from inclusive and like-sign dimuon samples:

$$A^b_{sl} = (+0.94 \pm 1.12\,(\text{stat}) \pm 2.14\,(\text{syst})\,)\% \quad (\text{from inclusive})$$

$$A^b_{sl} = (-0.736 \pm 0.266\,(\text{stat}) \pm 0.305\,(\text{syst})\,)\% \quad (\text{from dimuon})$$

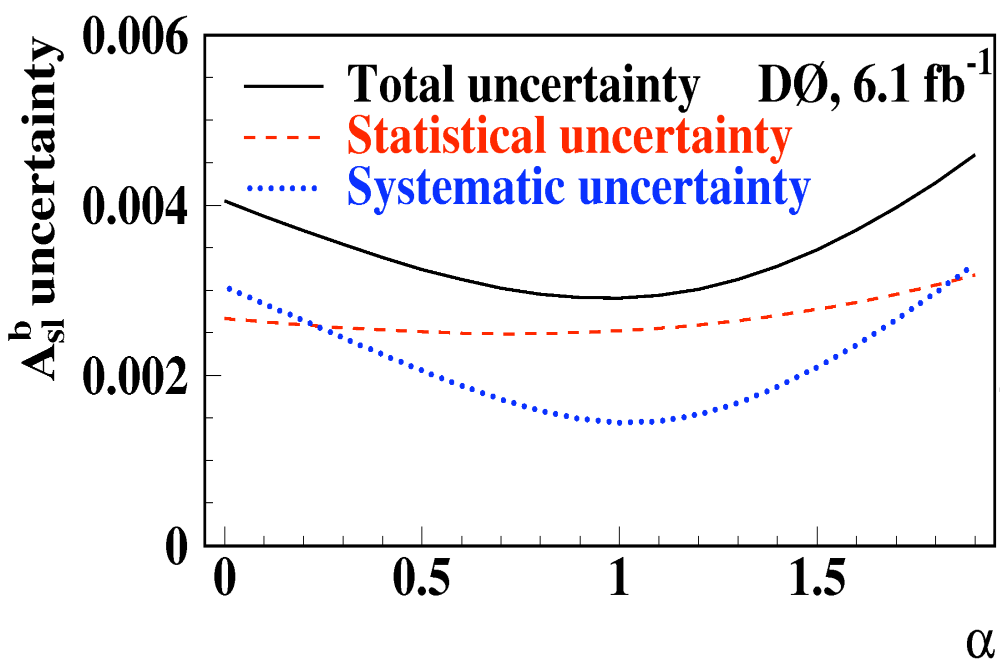
- Uncertainties of the first result are much larger, because of a small coefficient $k = 0.041 \pm 0.003$
- Dominant contribution into the systematic uncertainty comes from the measurement of f_K and F_K fractions



Combination of Measurements

- Single muon asymmetry completely dominated by background, and background systematic is dominant
- Obtain the final result using the linear combination:

$$A' \equiv A - \alpha\, a = (K - \alpha\, k) A_{sl}^{b} + (A_{bkg} - \alpha\, a_{bkg})$$



Since $A_{bkg} \approx a_{bkg}$ and the uncertainties of these quantities are correlated, we can expect the cancellation of background uncertainties in A' for $\alpha \approx 1$

The signal asymmetry A^b_{sl} does not cancel in A' for $\alpha \approx 1$ because k<<K

Final result

- From $A' = A - \alpha a$ we obtain a value of A^b_{sl} :

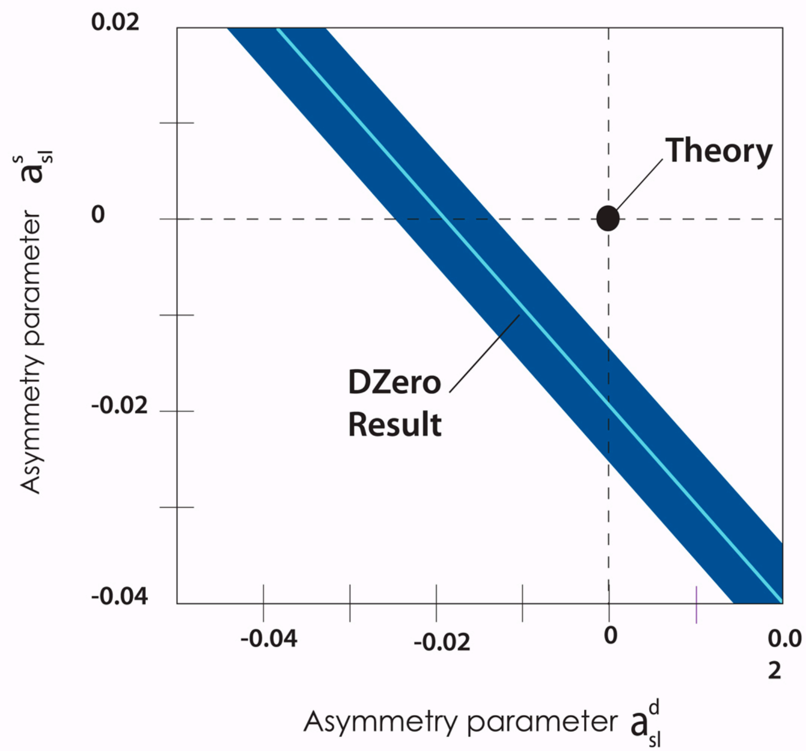
$$A^b_{sl} = (-0.957 \pm 0.251\,(\mathrm{stat}) \pm 0.146\,(\mathrm{syst})\,)\%$$

- To be compared with the SM prediction:

$$A^b_{sl}(SM) = (-0.023^{+0.005}_{-0.006})\%$$

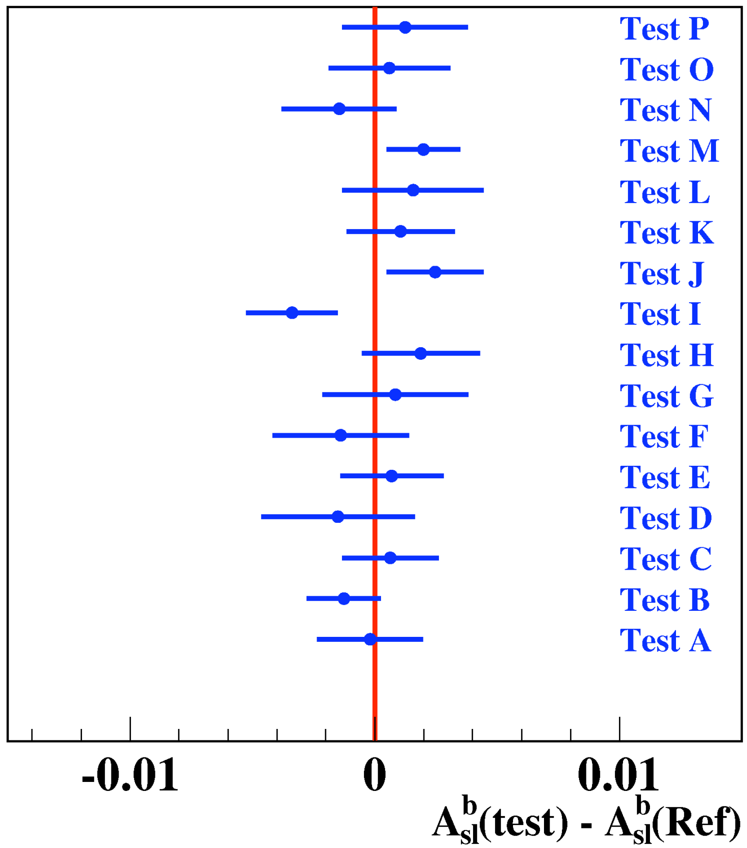
- This result differs from the SM prediction by ~3.2 σ
- Previous measurement

$$A_{SL} = (-0.92 \pm 0.44 \pm 0.32)\%$$



Consistency Tests

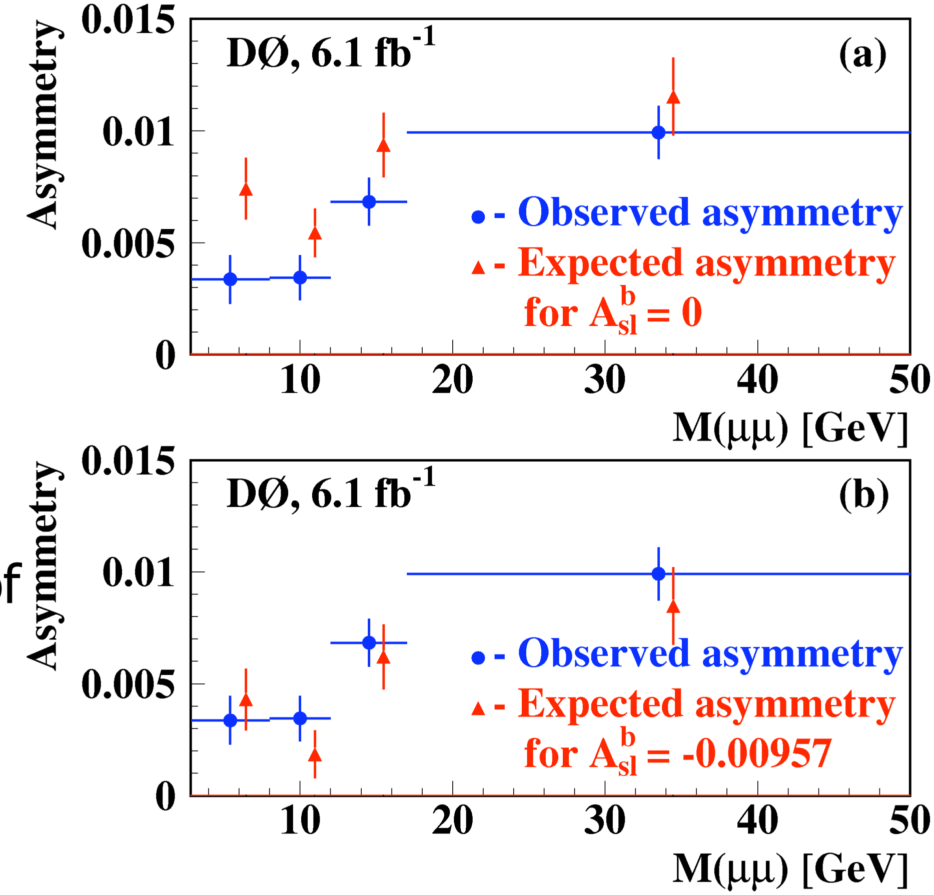
- We modify selection criteria, or use a part of sample to test the stability of result
- 16 tests in total are performed
- Very big variation of raw asymmetry A (up to 140%) due to variation of background, but A^b_{sl} remains stable



Developed method is stable and gives consistent result after modifying selection criteria in a wide range

Dependence on Dimuon Mass

- We compare the expected and observed dimuon charge asymmetry for different masses of $\mu\mu$ pair
- The expected and observed asymmetries agree well for $A^b_{sl} = -0.00957$
- No singularity in the *M(μμ)* shape supports B physics as the source of anomalous asymmetry



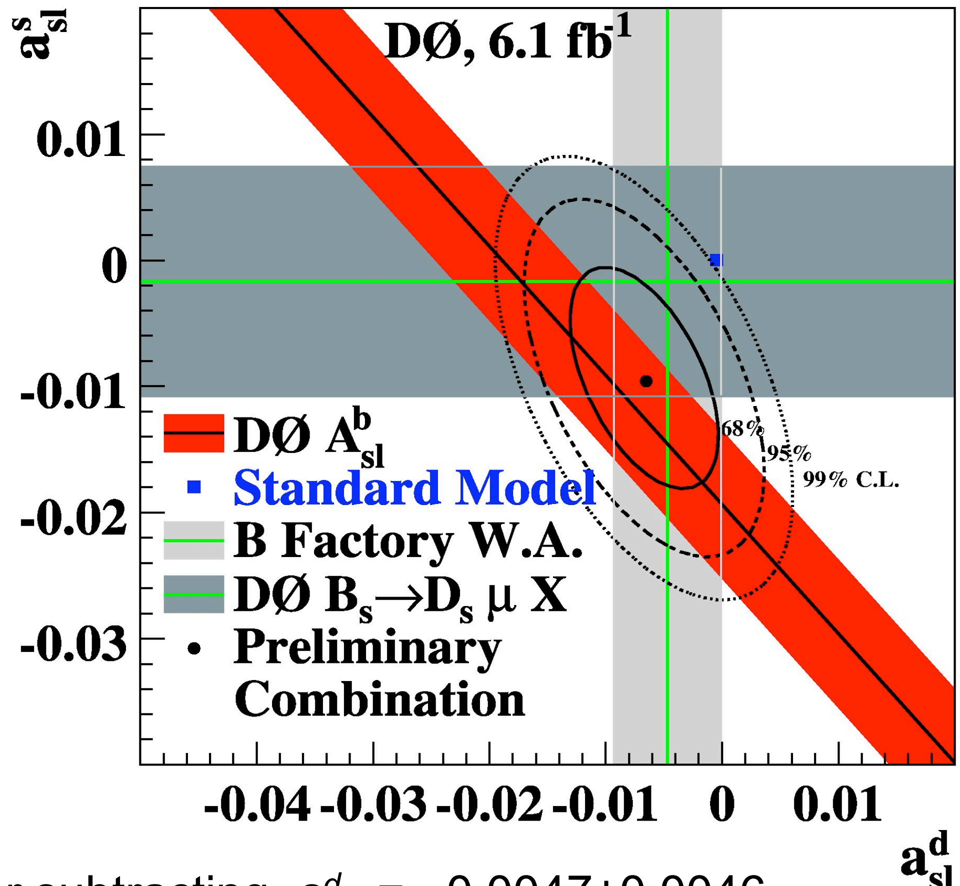
D0 Combination of a^s_{sl}

- Obtained result agrees well with other D0 measurements of a^s_{sl} and world average of a^d_{sl}

- D0 combination of all measurements of semileptonic charge asymmetry

$$a^s_{sl} = (-1.46 \pm 0.75)\%$$

$$a^s_{sl}(SM) = (+0.0021 \pm 0.0006)\%$$

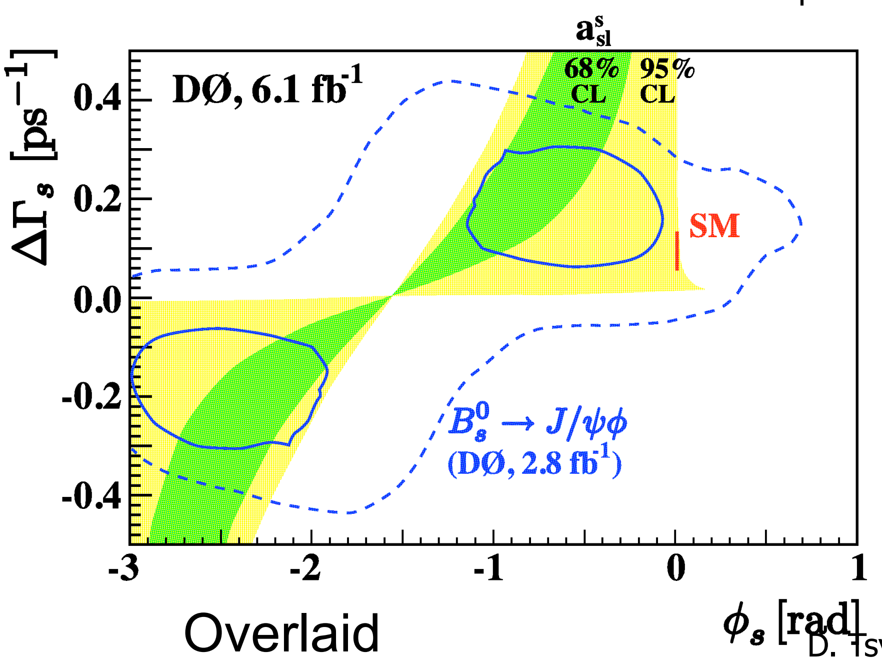


After subtracting $a^d_{sl} = -0.0047 \pm 0.0046$ measured at B factories

Comparison with other measurements

- Obtained value of a^s_{sl} can be translated into the measurement of the CP violating phase ϕ_s and $\Delta\Gamma_s$
- This constraint is in excellent agreement with an independent measurement of ϕ_s and $\Delta\Gamma_s$ in $B_s \rightarrow J/\psi\phi$ decay

$$A^s_{SL} = \mathrm{Im}\frac{\Gamma_{12}}{M_{12}} = \left|\frac{\Gamma_{12}}{M_{12}}\right| \sin\varphi_s = \frac{\Delta\Gamma_s}{\Delta m_s} \cdot \tan\varphi_s$$



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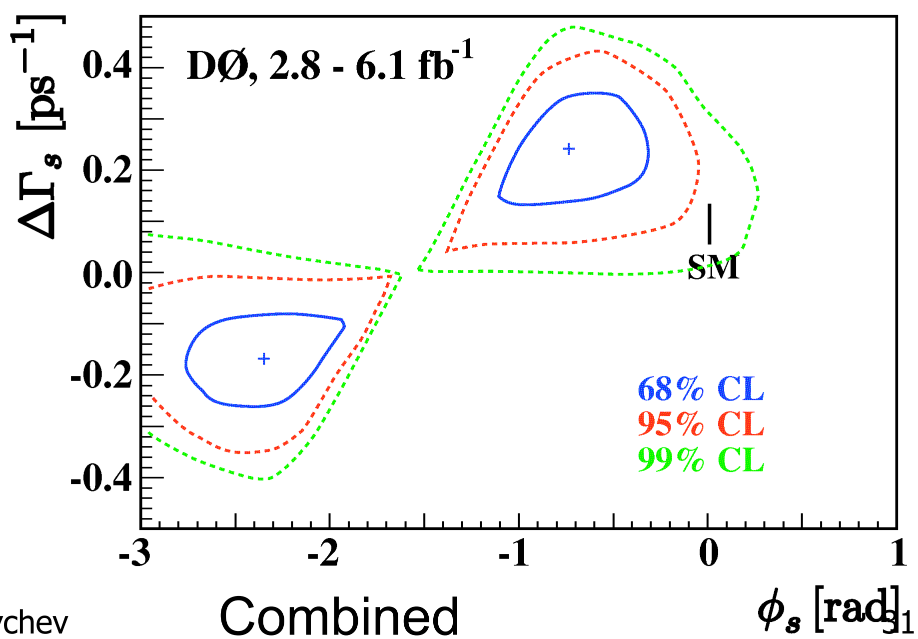


Combined

Summary and Conclusions

- New measurement of A^b_{sl} is performed

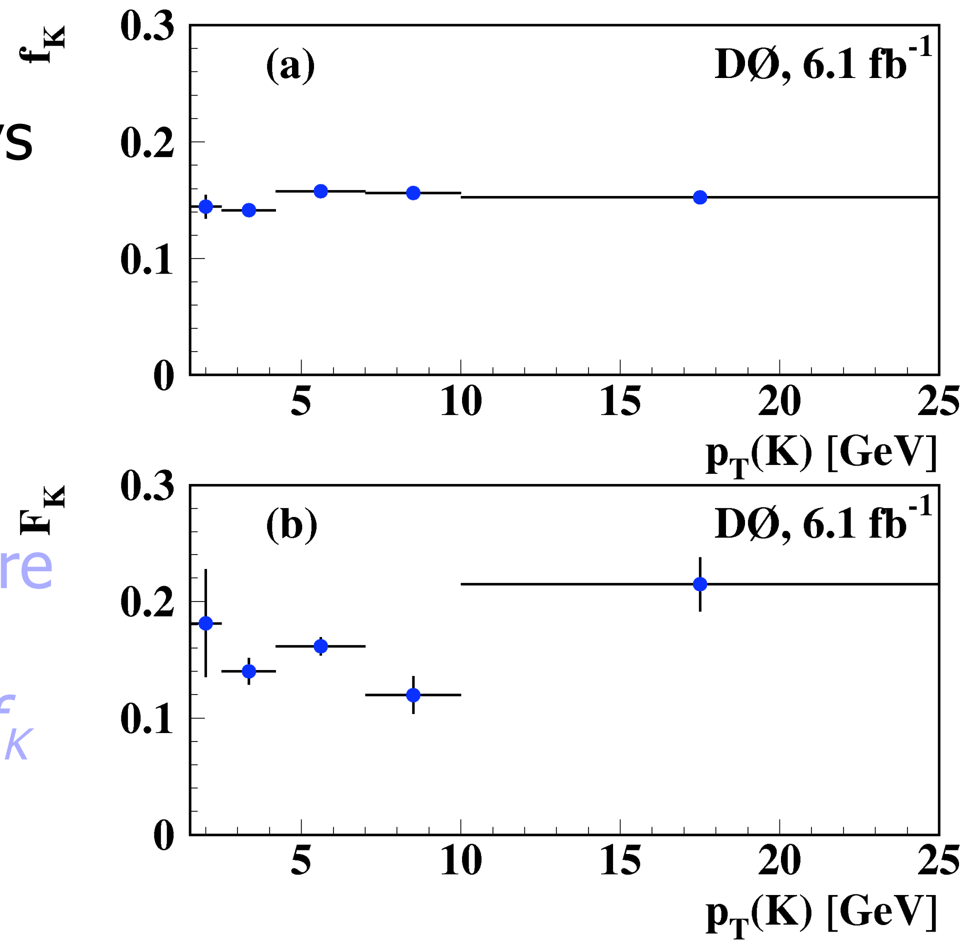
$$A^b_{sl} = (-0.957 \pm 0.251\,(\text{stat}) \pm 0.146\,(\text{syst}))\%$$

  - Submitted to arXiv:1005.2757
- Almost all relevant quantities are obtained from data with minimal input from simulation
  - Closure test shows good agreement between expected and observed asymmetries in the inclusive muon sample
- This asymmetry is not consistent with the SM prediction at a 3.2σ level
  - We observe that the number of produced particles of matter (negative muons) is larger than the number of produced particles of antimatter
  - Dominant uncertainty is statistical – precision can be improved with more luminosity!
- May see sign of new physics at LHC soon!

Backup

Kaon Fractions f_K, F_K

- Fractions f_K , F_K are measured using the decays $K^{*0} \to K^+\pi^-$
- We measure f_{K^*0} , F_{K^*0}
- We find f_{K^*0}/f_K using the similar decay $K^{*+} \to K_S\pi^-$
  - In this decay we measure f_{K^*+}/f_{Ks} and convert it into f_{K^*0}/f_K



Statistical and Systematic Uncertainties

Source	A^b_{sl} inclusive muon	A^b_{sl} dimuon	A^b_{sl} combined
A or a (stat)	0.00066	0.00159	0.00179
f_K or F_K (stat)	0.00222	0.00123	0.00140
$P(\pi \to \mu)/P(K \to \mu)$	0.00234	0.00038	0.00010
$P(p \to \mu)/P(K \to \mu)$	0.00301	0.00044	0.00011
A_K	0.00410	0.00076	0.00061
A_π	0.00699	0.00086	0.00035
A_p	0.00478	0.00054	0.00001
δ or Δ	0.00405	0.00105	0.00077
f_K or F_K (syst)	0.02137	0.00300	0.00128
π, K, p multiplicity	0.00098	0.00025	0.00018
c_b or C_b	0.00080	0.00046	0.00068
Total statistical	0.01118	0.00266	0.00251
Total systematic	0.02140	0.00305	0.00146
Total	0.02415	0.00405	0.00290

Dominant uncertainties

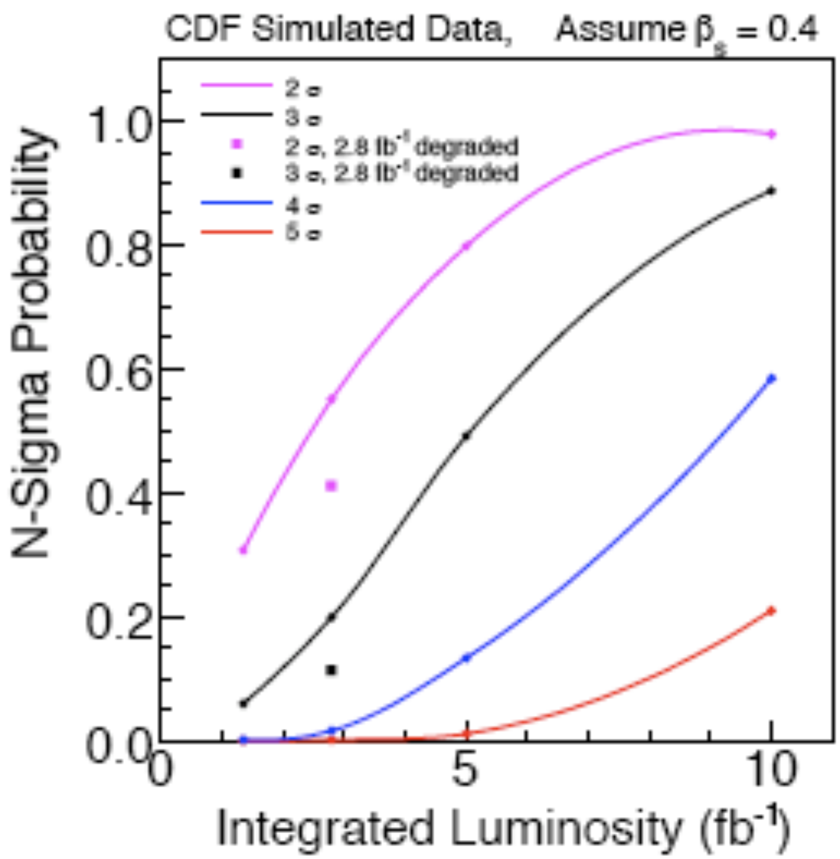
Outlook

Both CDF and DØ observe 1-2 sigma deviations in ϕ_s from SM predictions

Combined result 2.12σ w.r.t SM expectation

Interesting to see how these effects evolve with more data

Updated analyses from both CDF and D0 expected soon



Presented at Moriond 2010